(2)

Report No. CG-D-16-86

AN EVALUATION OF THE HYPOTHESIS THAT LASER LIGHT IS MORE CONSPICUOUS THAN INCANDESCENT LIGHT

AD-A170 823

T.S. WINSLOW
AND
M.B. MANDLER

U.S. COAST GUARD RESEARCH AND DEVELOPMENT CENTER
AVERY POINT, GROTON, CONNECTICUT 06340-6096

FINAL REPORT
MAY 1986

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for:

U.S. Department Of Transportation
United States Coast Guard
Office of Research and Development
Washington, DC 20593

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein soley because they are considered essential to the object of this report.

The contents of this report reflect the views of the Coast Guard Research and Development Center, which is responsible for the facts and accuracy of data presented. This report does not constitute a standard, specification, or regulation.

SAMUEL F. POWEL, III
Technical Director
U.S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340

Technical Report Documentation Page

1. Report No. CG-D-16-86	2. Government Accession No. ADA 170823	3. Recipient's Catalog No.
4. Title and Subtitle AN EVALUATION OF THE HYPOTHESIS THAT LASER LIGHT IS MORE CONSPICUOUS THAN INCANDESCENT LIGHT		5. Report Date May 1986
		6. Performing Organization Code
7. Author(s) T.S. Winslow, M.B. Mandler		8. Performing Organization Report No. CGR&DC 8/86
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center Avery Point Groton, Connecticut 06340-6096		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Research and Development Washington, D.C. 20593		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code G-DST-1
15. Supplementary Notes		

16. Abstract

It has been thought that laser aids-to-navigation might appear more conspicuous than aids employing conventional light sources. Two experiments rigorously tested the hypothesis that laser light is more conspicuous than incandescent light. Incandescent and Helium-Neon laser sources were optically filtered and adjusted to present the same illuminance and color to distant observers. Thirty-seven observers viewed 60 random presentations (2 source types, 2 illuminance levels) from a distance of 1500 yards. Group correct source discrimination percentages were 52.6 and 55.2 for the low and high illuminance levels, respectively. The experiment was repeated indoors at higher illuminances with resultant group correct source discrimination percentages of 57, 67.5, and 66 for the low, medium, and high illuminances, respectively. It was concluded that at "practical" design illuminance levels, no significant conspicuity advantage would be gained by replacing existing navigational aids with laser aids-to-navigation. Calculations show that a significant conspicuity advantage is likely to be obtained if the mariner uses a narrow bandpass filter (3-10 nm) centered at the laser wavelength. The illuminance from the laser will be relatively unaffected, while the illuminances from all background lights will be dramatically diminished.

An additional section compares the electrical efficiency of a standard Coast Guard FA-240 range light with a laser aid configured for the same application. For equal input power, the FA-240 is shown to produce 10 times the luminous intensity of the laser aid.

17. Key Words aids to navigation lasers conspicuity visual discrimination	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) UNCLASSIFIED	20. SECURITY CLASSIF. (of this page) UNCLASSIFIED	21. No. of Pages	22. Price

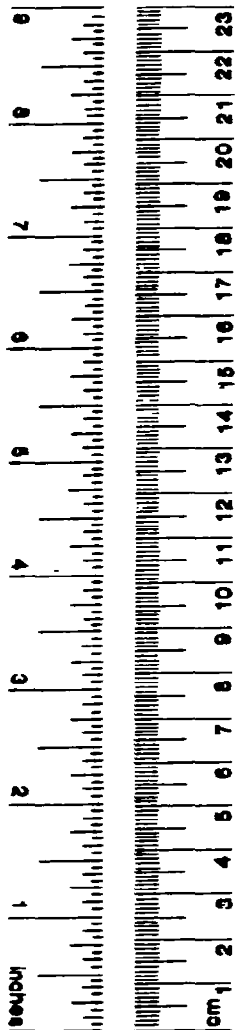
Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

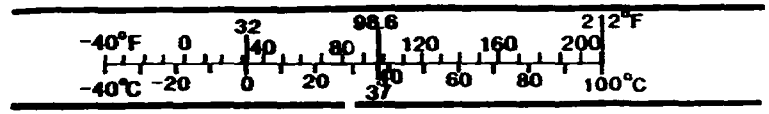


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ACKNOWLEDGEMENT

We gratefully acknowledge the contributions of Robert E. Stachon in designing and building the apparatus and carrying out the photometric measurements.

INTRODUCTION

One of the most serious problems facing mariners attempting to navigate safely in coastal or landlocked waters is that of background lighting. Shore lighting (streetlights, automobile lights, illuminated signs, etc.) is the subject of universal complaints by both professional marine pilots and amateur boaters alike. Under commonly occuring conditions when lighted aids-to-navigation are superimposed on a background consisting of thousands of shore lights, it can be extremely difficult to differentiate the relevant aids from the background. Color and pulse coding of lighted aids provides some improvement; however, shore lights are often of similar colors and may flash or appear to flash due to relative motion between the observer and the source. A Working Group of the National Academy of Sciences - National Research Council (Reference 1) suggested that this problem could be alleviated in the short term by developing new types of signals that were more conspicuous, and in the long term by regulating the shore lights that interfere with navigation.

The U. S. Coast Guard has always sought to design, build, and deploy new types of hardware to present more conspicuous signals. For several years lasers were promoted as a possible solution to the background lighting problem. Inherent laser properties (monochromaticity, high spectral radiance,and coherence) were thought to be advantages of laser sources; specifically, diffraction phenomena (as a consequence of the coherence) were suspected of giving a unique appearance to a distantly observed laser source, enabling it to stand out from other lights in the background.

The Coast Guard embarked on a program to develop prototype laser navigational aids (LANAIDS) in 1980; a contract was awarded to Xerox Electro-Optical Systems (XEOS) to develop, test, and demonstrate two LANAIDS - a rotating beacon and a single-station range light. During field tests of the laser prototypes in Los Angeles Harbor, it was noted that the LANAIDS appeared different from other operational aids-to-navigation when observed from distances up to a few miles (Reference 2). A second contract was awarded to

Xerox (now Loral) Electro-Optical Systems to modify the two prototypes and correct some system deficiencies. The contract included a laser conspicuity study to examine the potential signal improvement realizable with a laser source (Reference 2, Appendix A). It was noted from visual observation that the LANAID range light (incorporating both Helium-Neon and Helium-Cadmium lasers) produced beams with apparent diameters much larger than their actual exit apertures (referred to as "blooming"). During these observations, the laser signals were also judged to have a discernible internal structure, with the term "graininess" used by some of the observers to describe the appearance (Reference 2). This structure was attributed to "speckle", a diffraction phenomenon arising from coherence. Similar observations were made at the Coast Guard Research and Development Center in uncontrolled laboratory and field settings. These observations further supported the belief that lasers might offer conspicuity advantages over incandescent sources.

As part of a multiyear effort to quantify the effectiveness of visual signals used in aids-to-navigation and develop more effective visual signals, a rigorous evaluation of laser conspicuity was conducted. The previous work with the prototypes depended too heavily upon subjective observation, rather than empirically testing the hypothesis that laser light is more conspicuous than incandescent light. The subsequent evaluation is based on the hypothesis that to be more conspicuous than incandescent light, laser light MUST differ in appearance from incandescent light. A significant difference in appearance should allow observers to reliably discriminate between the two light sources; this ability to discriminate can be rigorously evaluated. Incandescent sources can be filtered and focused to produce light output somewhat similar to that of lasers - highly monochromatic and of very high spectral radiance. Any discriminable difference between a laser signal and a properly conditioned incandescent signal then presumably can only be a consequence of the unique laser property, coherence, and perhaps the resultant "speckle". That laser light exhibited observable "speckle" was never questioned; however, whether or not this effect contributed to increased signal conspicuity was unknown.

Two experiments were conducted to measure observers' abilities to discriminate between laser and incandescent sources. Both sources were equipped with the appropriate lenses and filters to obtain close matches of color and illuminance at the observer location. These characteristics were not controlled in the previous observations. (The judged conspicuity advantage of laser light may have resulted merely from having a higher illuminance at the observer location than the incandescent lights under observation.) In the field experiment, using illuminance levels representative of those encountered during shipboard piloting, 37 observers correctly discriminated between the two sources slightly better than half the time. In the laboratory experiment, performance improved with increasing illuminance, but the best performance by 10 observers was 67.5% correct discriminations, still a rather poor performance given the ideal laboratory conditions. Under marine piloting conditions, at illuminance levels compatible with typical aids-to-navigation system design, laser sources cannot be expected to offer significant conspicuity advantages over incandescent sources.

However, with the use of an inexpensive narrow bandpass filter, the mariner can greatly reduce illuminance from background lights while leaving illuminance from the laser source relatively unchanged. The laser source will be very conspicuous when viewed with the aid of a properly selected filter. In an additional section, calculations are provided which compare the luminous intensity of an existing FA-240 range lantern to the theoretical intensity for a similarly configured Helium-Neon laser system for equal electrical input power; the incandescent FA-240 is shown to be several times more efficient.

METHOD

As mentioned above, previous comparisons of the LANAIDS and standard Coast Guard aids-to-navigation hardware fitted with incandescent lamps were not conducted under controlled conditions - the confounding effects of variables such as source illuminance and color were not effectively eliminated from the experiments. A transportable setup was configured which incorporated laser

and incandescent sources matched closely in color and illuminance at the observer location. The Helium-Neon laser was chosen for convenience and due to the large number of red navigation lights in operational use. The diffraction-limited laser output beam was directed through a diverging lens to produce a larger exit aperture and greater beam divergence. A 300-Watt Tungsten-Halogen lamp was used as the incandescent source. A small parabolic reflector in the lamp housing directed the lamp output into the end of a cylindrical tube to eliminate off-axis radiation. The exit end of the tube was fitted with a 3 nanometer (nm) full-width half-maximum (FWHM) narrow bandpass filter centered at 632.8 nm (Helium-Neon wavelength). In this region of the visible spectrum, the human eye/brain cannot discriminate between wavelength differences as small as 3 nm (Reference 3), so the two appeared to be identical in color. In the initial setup, a 10 nm (FWHM) filter was found to be inadequate due to a color difference between the incandescent and laser sources.

With the color closely matched, neutral density filters were inserted in the optical path of the laser to reduce its apparent illuminance to approximately that from the incandescent source. Then, with a calibrated photometer located 22 meters from the two sources, the illuminance from each beam was monitored as the source outputs were finely tuned by the addition of incremental neutral density filters. The beam illuminances were matched to within 5% (illuminance was checked at several points within a field 2 meters in diameter). Figure 1 depicts the experimental setup.

The maximum illuminance obtainable was 61,203 sea-mile-candles (smc) at 22 meters. At the planned field observation range of 1372 meters, this corresponded to an illuminance of 14.5 smc, assuming a transmissivity of 0.9. The visual threshold for the field location was assumed to be 6.7 smc (clear night with minor background lighting, Reference 4). At 14.5 smc the sources would have been detectable, though the range of available illuminances (above threshold) would have been too narrow to measure discrimination as a function of illuminance. The incandescent lamp was replaced with a 250-Watt xenon arc

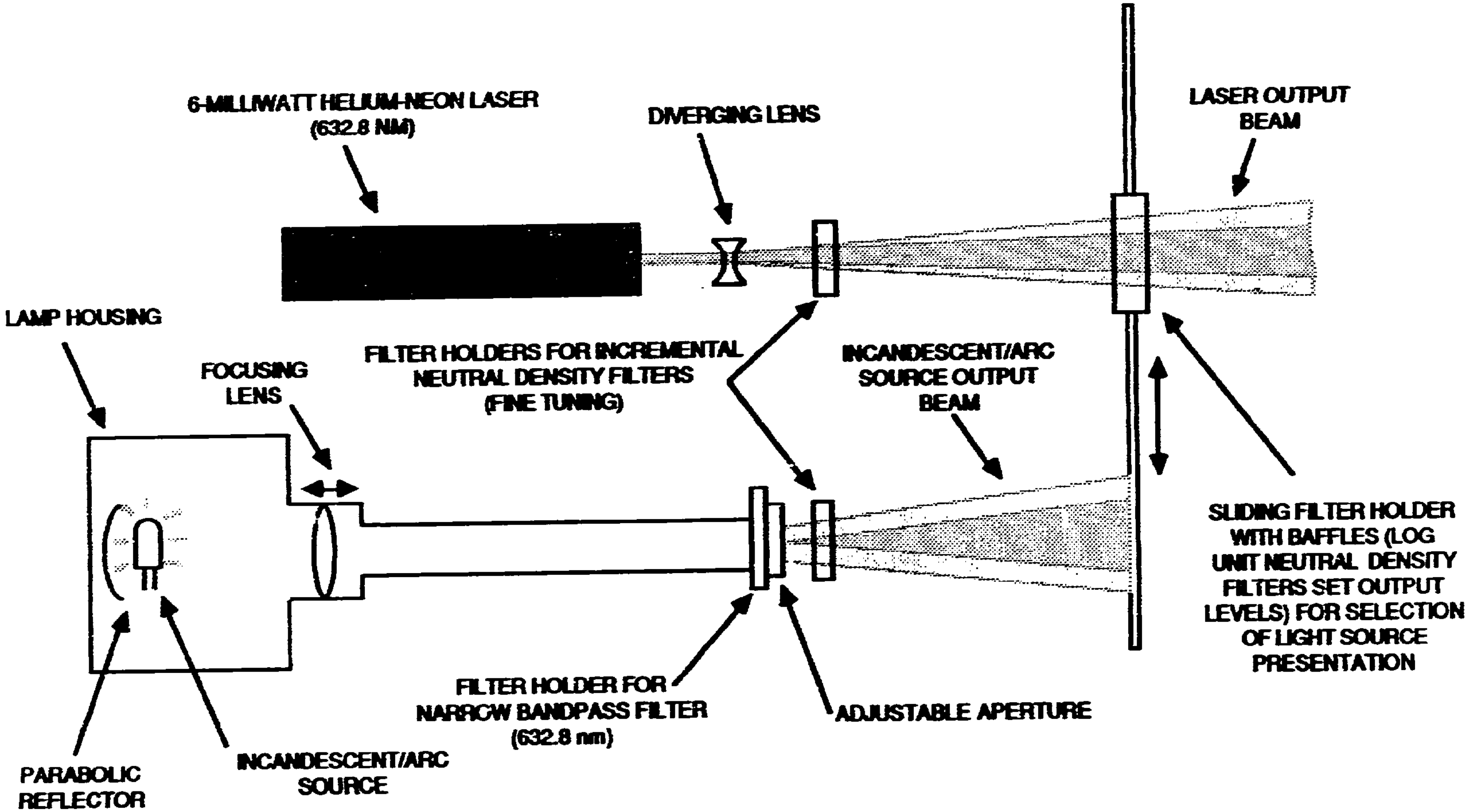


FIGURE 1. SCHEMATIC OF TRANSPORTABLE LASER/INCANDESCENT SOURCE SETUP

lamp to achieve higher illuminance. (Over the very narrow bandwidth of the red filter, small spectral output differences between the arc lamp and incandescent lamp were inconsequential.) The procedure previously described was repeated with the arc lamp to achieve two beams with closely matched illuminances at the photometer, 22 meters from the sources. The exit apertures of the laser and arc lamp sources were approximately 1.5 cm and 3.0 cm, respectively; at 1372 meters, both appeared as point sources.

For the field test, the sources and associated equipment were transported to a site across the Thames River from the Coast Guard Academy in Groton, CT. The observations were made on a very clear night with no moonlight; however, there was a small amount of skylight (scattered light from nearby industrial and city lighting). A few streetlights and residential lights dotted the background at the source location. Thirty-seven (37) cadets observed the sources from the Academy 1372 meters away. Two levels of illuminance (10.9 and 1086 smc) were used; source and illuminance level were randomly varied for a total of 60 presentations (37 observers x 60 presentations = 2220 observations). The subjects were given several trial runs at both illuminance levels with both sources to familiarize them with the different presentations. After each observation, the cadets were asked to decide which source had been presented and record their determinations. After the choices had been made, the subjects were told which source had been presented.

The higher level of illuminance in the field test did not cause the "blooming" effect that had been previously observed in lasers. It was thought that at sufficiently high illuminance levels, the laser might gain some advantage due to this effect. To test this possibility, similar observations were made in the laboratory at closer ranges. The incandescent lamp was installed, and the two sources matched within 5% illuminance at the observer location. The difference in exit aperture diameters was immediately apparent, and the incandescent was fitted with an adjustable aperture to reduce its output beam diameter to that of the laser. Observations were made at three illuminance levels - 612, 6120, and 61203 sea-mile-candles. Again, the source

presentations were made randomly, and the observers were told which source had been presented after each of 60 trials. The experiment was conducted in a totally dark laboratory space - the visual threshold was significantly lower than the "practical" threshold of 0.67 sea-mile-candles (clear, dark night with observer moderately dark-adapted, Reference 4).

RESULTS AND DISCUSSION

In the field test, 37 cadets were shown 60 presentations (2 illuminance levels and 2 sources) at an observation distance of 1372 meters. Table I shows the group percent correct discriminations and standard errors.

TABLE I

FIELD TEST SOURCE DISCRIMINATION PERFORMANCE

	Low Illuminance (10.9 smc)	High Illuminance (1086 smc)
Percent Correct	52.6	55.1
Standard Error	1.52	1.87

The results were tested for statistical significance at a confidence level of 95%. The t-statistics, with 36 degrees of freedom, were 1.71 and 2.73 for the low and high illuminance conditions, respectively. The high illuminance discrimination performance was thus shown to be significantly better than that to be expected from chance, while the low intensity discrimination performance was not.

In the laboratory test, 10 observers were shown 60 presentations (3 illuminance levels and 2 sources) at a distance of 22 meters. Table II displays the group percent correct discriminations and standard errors.

TABLE II

LABORATORY TEST SOURCE DISCRIMINATION PERFORMANCE

	Illuminance		
	Low (612 smc)	Medium (6120 smc)	High (61203 smc)
Percent Correct	57.0	67.5	66.0
Standard Error	4.73	5.51	6.47

The laboratory results were tested for statistical significance at a confidence level of 95%. The t-statistics, with 9 degrees of freedom, were 1.48, 3.17, and 2.47 for the low, medium, and high illuminance conditions, respectively. The medium and high illuminance discrimination performances were found to be significantly better than that to be expected from chance, while the low illuminance discrimination performance was not. The raw data for both experiments are tabulated in Appendix A.

During the field and laboratory observations, extreme care was taken to eliminate possible cues (introduced as a result of the experimental technique) which might be used by the observers to improve performance. Nevertheless, occasional comments from the observers indicated some possible influence of this type. In the laboratory experiment, a few observers claimed to use source lateral position as a cue (the source apertures were not collocated, but were approximately 4 inches apart). To limit the effectiveness of this cue, the observers were disoriented by requiring them to sit facing 90 degrees from the observer-source axis and turn to view each source presentation only when prompted. Each presentation was limited to three seconds duration.

The data show that discrimination between coherent (laser) and incoherent (incandescent) light improves with increasing illuminance at the observer location. The medium and high illuminance levels used in the laboratory resulted in higher percentages of correct discrimination than the two field illuminance levels. The illuminance levels used in the field test are more

representative of those encountered in comparable aids to navigation. For example, an FA-240 range lantern with a 1.15-Amp lamp and red 3.5° Spreadlite lens produces an illuminance at two miles of 616 smc, assuming a transmissivity of 0.75. The original premise of these experiments was that two light signals must LOOK different if one is to have a potential conspicuity advantage over the other. Thus, if a laser source looks different from an incandescent source, then a laser placed in a harbor with significant incandescent background lighting should be more conspicuous (easier to detect and identify) than an incandescent source producing equal illuminance in that same harbor location. Given that the discriminations in these experiments were difficult (observers reported they often guessed), and the best performance resulted in only 67.5% correct discriminations (assuming no influence from cues), it is not clear that a significant conspicuity advantage could be obtained using practical aids-to-navigation design parameters. The high illuminances at which the discriminations were significantly better than chance are only encountered at short ranges. Glare becomes a problem at these illuminances, affecting the state of dark adaptation and limiting ability to detect objects near the glare source. When the illuminances of the sources were such that glare was not a problem, as in the field test and at the lowest laboratory illuminance, discrimination was poor.

USING A BANDPASS FILTER

The Coast Guard has considered (Reference 2) the use of narrow wavelength bandpass filters, by the mariner, to selectively filter out background lighting while leaving the illuminance from lighted aids within the passband relatively unchanged. An electrical analog is the attenuation of "noise" so that the signal of interest stands out, thereby increasing the signal-to-noise ratio. This concept has particular merit with laser sources due to their high degree of monochromaticity. A multimode Helium-Neon laser has a full spectral width of less than 0.01 nm; in comparison, a typical incandescent lamp has a spectral width about five orders of magnitude greater (Reference 2). A very narrow bandpass filter centered at the laser wavelength would greatly diminish the illuminance from light sources in the background while diminishing that

from the laser aid-to-navigation a much lesser amount. Sources already filtered to give outputs of specific colors (except red) would likely appear to be completely extinguished. It is worth noting that white lights would appear reddish, albeit with greatly reduced illuminances. The overall effect of the filter would be to facilitate detection and identification of a laser aid-to-navigation when entering a large harbor with many competing lights in the background.

Jacobs (Reference 2) calculated the theoretical illuminance difference between a 200-Watt incandescent lamp and a 5-Milliwatt Helium-Neon laser when both are viewed through a 10 nm narrow bandpass filter. With the laser diverged to form a 10 mrad square beam and the incandescent assumed to be radiating equally in all directions, the laser was predicted to produce 640 times the illuminance of the incandescent lamp (Reference 2). The assumption of an incandescent lamp radiating equally in all directions is reasonable, since most background lights (streetlights, traffic lights, illuminated windows, etc.) would not tend to be focused or directed optimally toward the shipboard observer. However, the 10 mrad square beam, although representing the actual divergence of a prototype laser aid-to-navigation tested by the Coast Guard, is too narrow to provide practical coverage in a typical range light scenario. A more useful beam measuring 20 mrad vertically by 40 mrad horizontally would still result in an illuminance from the laser of approximately 63 times that from the incandescent lamp.

The above calculations were validated by conducting photometric measurements of various types of sources with and without each of two narrow wavelength bandpass filters in place. The illuminance readings from the calibrated photometer were then used to calculate ratios of filtered intensity to unfiltered intensity for each source. (Since intensity is independent of distance, it is a more convenient photometric unit for this analysis.) Table III shows the percentage of original intensity measured for the various sources when the 3 nm and 10 nm filters were used. (Filters used have a maximum transmittance of approximately 50%.)

TABLE III

MEASURED INTENSITY USING NARROW BANDPASS FILTERS AS A PERCENTAGE OF UNFILTERED INTENSITY FOR VARIOUS LIGHT SOURCES

Source Type	Rated Power (Watts)	% Intensity (10 nm)	% Intensity (3 nm)
Tungsten-Halogen	1000	2.158	0.676
Metal Halide	400	0.994	0.207
Mercury Merculite	500	0.747	0.194
Sodium (High Pressure)	35	1.048	0.221
Helium-Neon Laser (Multimode)	.006	56.442	53.374

The measured sources are typical of those used for residential and commercial lighting in and around harbor areas. The intensity ratios can now be used to calculate with a high degree of confidence the effect of the bandpass filters on similar sources. The IES Lighting Handbook-1981 (Reference 5) was consulted to find the luminous flux (lumens) from commonly used sources. These were assumed to be radiating equally in all directions, and the resultant luminous intensity was calculated for each source. A special case was also considered for spot and flood lights with concentrating parabolic reflectors. Luminous flux after the initial "burning in" period was used in the calculations, and the background lights were assumed to suffer no light losses from dirty lenses or luminaires, atmospheric attenuation, or voltage/current drops. Table IV shows the light source data and luminous intensities/ratios for the 3 nm filter.

TABLE IV

LIGHT SOURCE DATA AND LASER/SOURCE INTENSITY RATIOS
FOR TYPICAL BACKGROUND LIGHTS

Source	Watts	Lumens	Original Intensity (candela (cd))	3 nm Intensity (cd)	Laser/Source Intensity Ratio
Metal Halide	400	25000	1990	4.12	43.2
Mercury	400	18000	1433	2.78	64.0
Sodium (High Pressure)	400	43000	3424	7.57	23.5
Sodium (Low Pressure)	180	30000	2389	5.28*	33.7*
Tungsten Halogen	1000	23000	1831	12.38	14.4
Incand. Street	500	9000	717	4.85	36.7
Tungsten-Halogen Flood** (Type R lamp - 10 degree cone)	1000	--	15500	104.80	1.7
Tungsten-Halogen Spot** (Type R lamp - 5 degree cone)	1000	--	135000	912.60	0.2
HeNe Laser	6-mWatt	--	335	178.00	1.0

* filter ratio from high pressure sodium used.
** intensity average over cone.

The flood light is nearly as intense, and the spot light is about 5 times as intense, as the laser when observed on-axis; however, it is considered highly unlikely that the concentrated incandescents would be viewed in this manner. The laser is from 14 to 64 times as intense as the other sources, depending on the source in question. The majority of lights in the background will have much lower intensities due to several factors - lower wattage, light losses from dirty luminaires, atmospheric attenuation, etc. Thus, laser/source intensity ratios to be expected with the filter will be greater than those in Table IV.

EFFICIENCY

Light sources normally are compared in terms of intensity or illuminance; in Coast Guard applications, the luminous intensity as a function of electrical power is of particular interest due to the increasing use of photovoltaic power on lighted aids-to-navigation. It is instructive to compare an existing aid-to-navigation with a Helium-Neon laser configured for the same application. An FA-240 range lantern fitted with a clear 3.5 degree Spreadlite lens and 1.15-Amp Tungsten-Halogen lamp (12VDC) was measured in the laboratory and found to have the following output beam characteristics:

Peak Intensity	13274 candela (cd)
Horizontal Beamwidth	3.62 degrees (FWHM)
Vertical Beamwidth	2.64 degrees (FWHM)

The red Spreadlite lens normally results in a lantern intensity 33% of that obtained for the clear lens (Reference 6):

$$\text{Peak Intensity} = 0.33 \times 13274 \text{ cd} = 4380 \text{ cd}$$

The intensity at the edges of the beam is therefore 2190 cd. The lantern uses approximately 14 Watts of electrical power. A representative 6-milliwatt (output power) Helium-Neon laser consumes 15 watts of electrical power (Reference 7). The FA-240 horizontal and vertical beamwidths convert to 63.1 and 46.1 milliradians, respectively. The beam subtends a solid angle of:

$$0.0631 \text{ rad} \times 0.0461 \text{ rad} = 2.91 \times 10^{-3} \text{ steradians (sr)}$$

To produce similar geometric coverage, the laser beam must be diverged to subtend the same solid angle. The radiant intensity is then:

$$6 \times 10^{-3} \text{ Watts} / 2.91 \times 10^{-3} \text{ sr} = 2.06 \text{ Watts/sr}$$

At the laser wavelength (632.8 nm), the interpolated value for the relative luminous efficiency is 0.2381 (Reference 8). Maximum luminous efficacy is 683 lumens/Watt (Reference (9); the laser luminous intensity is then:

$$2.06 \text{ Watts/sr} \times 0.2381 \times 683 \text{ lumens/Watt} = 335 \text{ lumens/sr} = 335 \text{ cd}$$

For approximately equal electrical power inputs, the FA-240 lantern has ten times the luminous intensity of the diverged Helium-Neon laser. This is not a surprising result. A typical gas-filled Tungsten lamp has a luminous efficacy of 20 lumens/Watt (Reference 5), while the Helium-Neon laser has an efficacy of:

$$0.2381 \times 683 \text{ lumens/Watt} = 162.6 \text{ lumens/Watt}$$

However, the laser is extremely inefficient when converting electrical energy into radiant energy (the laser used as an example consumed 15 Watts, but converted only 6 Milliwatts into radiant energy). In general, existing aids-to-navigation are far more electrically efficient than potential laser aids-to-navigation.

CONCLUSIONS

- For an aid-to-navigation to be conspicuous, it must LOOK different from the background lights. At illuminance levels considered practical in the design of an integrated aids-to-navigation system, lasers cannot be distinguished from incandescent sources of the same color producing the same illuminance. This may be generalized to include comparisons between a laser and other commonly encountered incoherent sources - Tungsten-Halogen, metal halide, mercury, etc. At very high levels of illuminance, when glare became excessive, observers in the laboratory experiment could correctly discriminate between the laser and incandescent sources 67% of the time. These discriminations, however, were difficult even under ideal laboratory conditions where the observers were given practice and feedback. Therefore, it is concluded that a conspicuity improvement in lighted aids could not be achieved merely by replacing existing sources with lasers.

- If a bandpass filter of sufficiently narrow passband (3-10 nm), centered at the laser wavelength, is used to view a waterway, laser sources, by virtue of their illuminances, will be more conspicuous than the vast majority of background lights. The narrowband filter will reduce the perceived illuminances from the lasers by less than 50%, while all other lights would suffer reductions of at least 97% (greater than 99% if the 3 nm filter is used). In this mode of operation, observers can be expected to reliably discriminate between the laser and other sources. Narrow bandpass filters suitable for use with the Helium-Neon laser are inexpensive, "off-the-shelf" items from several optics manufacturers.

- It is clear that lasers are electrically inefficient; other types of sources are more suitable for applications where photovoltaic power is dictated.

- Unless the mandated use of narrow bandpass filters by mariners is considered a viable alternative, further development of aids-to-navigation hardware incorporating laser sources is not justified at this time.

REFERENCES

1. Benson, W., Brown, J. L., Douglas, C. A., Riney, J., Taylor, J. H., and Duntley, S. Q., "The Effects of Background Lighting on the Usefulness of Navigation Lights" (USCG Report, NTIS #AD732513), NAS-NRC Committee on Vision, Working Group 33, Washington, D. C., October 1971.

2. Jacobs, P. F., "Laser Aid to Navigation Final Report" (USCG Report, Contract # DTCG23-83-C-20004), Loral Electro-Optical Systems, Pasadena, CA, October 1984.

3. Graham, C.H. Vision and Visual Perception, John Wiley & Sons, Inc., New York, 1965.

4. U. S. Coast Guard Ocean Engineering Report No. 37 - "Visual Signalling: Theory & Application to Aids to Navigation" (CG-250-37), Ocean Engineering Division, USCG Headquarters, Washington, D. C., June 1970.

5. IES Lighting Handbook-1981, Illuminating Engineering Society of North America, Waverly Press, Inc., Baltimore, MD, 1981.

6. U. S. Coast Guard Ocean Engineering Report No. 12E - "Luminous Intensities of Navigational Aids" (CG-250-12E), Ocean Engineering Division, USCG Headquarters, Washington, D.C., March 1972.

7. Spectra Physics laser products brochure, 1985.

8. CIE Proceedings 1924, Cambridge University Press, Cambridge, MA, 1926.

9. CIE, The Basis of Physical Photometry, Publication No. 18, prepared by CIE Technical Committee TC-1.2, 1982.

APPENDIX A

RAW DATA

TABLE A-1
RAW DATA FROM FIELD OBSERVATIONS
(Percent Correct)

Observer	Illuminance Low	High
1	30.0 %	50.0 %
2	43.3 %	70.1 %
3	50.0 %	66.5 %
4	60.0 %	46.4 %
5	56.7 %	43.8 %
6	56.7 %	37.1 %
7	43.3 %	59.4 %
8	46.7 %	54.0 %
9	53.3 %	73.2 %
10	43.3 %	46.4 %
11	63.3 %	46.4 %
12	36.7 %	39.3 %
13	53.3 %	67.4 %
14	43.3 %	32.1 %
15	50.0 %	41.1 %
16	63.3 %	56.2 %
17	46.7 %	46.9 %
18	66.7 %	56.2 %
19	60.0 %	49.6 %
20	56.7 %	55.8 %
21	60.0 %	72.8 %
22	50.0 %	66.1 %
23	56.7 %	72.3 %
24	60.0 %	62.5 %
25	46.7 %	42.9 %
26	46.7 %	67.4 %
27	73.3 %	55.8 %
28	50.0 %	69.6 %
29	60.0 %	69.6 %
30	40.0 %	52.7 %
31	56.7 %	46.9 %
32	43.3 %	62.9 %
33	53.3 %	46.4 %
34	56.7 %	50.4 %
35	60.0 %	53.6 %
36	63.3 %	46.9 %
37	46.7 %	63.4 %
Mean	52.6 %	55.1 %
Standard Error	1.5 %	1.9 %

TABLE A-2
RAW DATA FROM LABORATORY OBSERVATIONS
(Percent Correct)

	Illuminance		
Observer	Low	Medium	High
1	65.0 %	70.0 %	90.0 %
2	50.0 %	75.0 %	55.0 %
3	65.0 %	55.0 %	80.0 %
4	50.0 %	50.0 %	65.0 %
5	85.0 %	75.0 %	35.0 %
6	60.0 %	45.0 %	55.0 %
7	30.0 %	70.0 %	65.0 %
8	50.0 %	100.0 %	100.0 %
9	55.0 %	80.0 %	65.0 %
10	60.0 %	55.0 %	50.0 %
Mean	57.0 %	67.5 %	66.0 %
Standard Error	4.5 %	5.2 %	6.1 %